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Experimental Evaluation of Cold-Sprayed Copper Rotating Bands for Large-Caliber Projectiles

by Michael A Minnicino

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Weapons and Materials Research Directorate, ARL

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14. ABSTRACT <p>A copper rotating band is the munition component responsible for both obturation and transfer of torque from the gun barrel's rifling to the munition, thereby causing the projectile to spin. Pure copper, copper alloy, and brass rotating bands are typically fabricated to steel munitions using the weld-overlay process, a radial-pressing process, or a thermal shrink fit. This paper documents the initial development and demonstration of a cold-sprayed copper rotating band in a 155-mm artillery system.</p>					
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1. Introduction

The copper rotating band is the projectile component responsible for both obturation and transferring torque from the gun-barrel rifling to the projectile, thereby causing the projectile to spin. The copper rotating band's location on a typical large-caliber munition is shown in Fig. 1. Traditional copper rotating bands are commonly manufactured by one of 2 methods: weld overlay and forging (i.e., radial pressing the rotating band onto the projectile). Forging the copper rotating band onto the munition is the preferred method for large production volumes. Weld overlay is a process in which one or more metals are applied to a base metal; it is sometimes referred to as “weld cladding” and is frequently employed in the installation of copper rotating bands on munitions produced in small quantities. However, the supersonic deposition, or cold-spray process, can be used for both large and small production volumes.

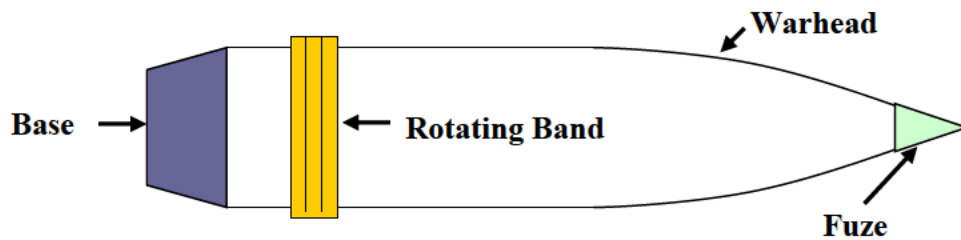


Fig. 1 Exterior features of a typical large-caliber munition

The cold-spray process is shown in Fig. 2. The cold-spray manufacturing process is an emerging technology that involves mixing micrometer-sized particles into a supersonic jet-gas stream to impinge them into the target surface and form either a coating or bulk material. The microparticles bombard the target surface at a velocity great enough to cause significant plastic deformation of both the microparticle material and target material, creating a strong mechanical–interfacial bond. As the process continues, the particulate material continues to mechanically bond to the substrate, resulting in a material with very low porosity. The nomenclature “cold spray” is used to describe this process due to the relatively low process temperatures (less than 100 °C). Unlike the overlay process, the cold-sprayed deposited materials can be applied to both metals and nonmetals. The cold-spray process is discussed in more detail by Champagne.¹

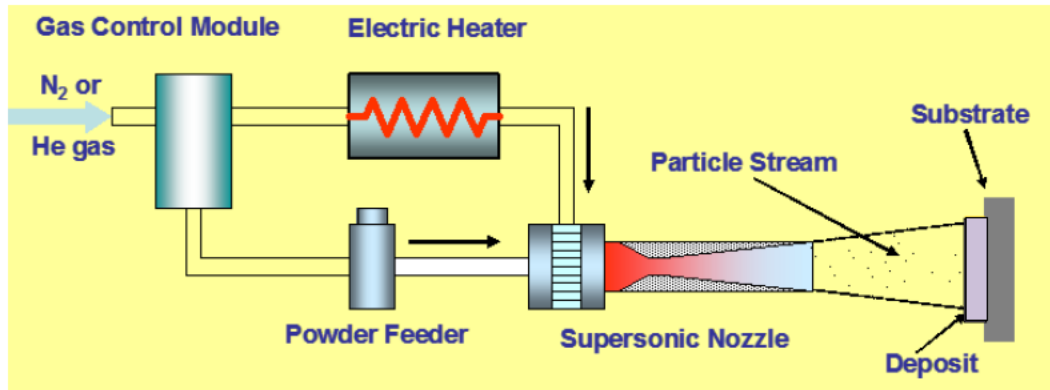


Fig. 2 Illustration of the cold-spray process using nitrogen (N₂) or helium (He) gas

Copper rotating bands are located on the rear portion of the munition and some rotating bands are located on the projectile's base, which is commonly fabricated from steel. An aluminum projectile base is desirable for several reasons that are the direct result of it being a lighter material than steel. The primary advantage of an aluminum base is that it translates the projectile's center of gravity forward, resulting in a more aerodynamically stable projectile. Another reason is the lighter aluminum base is more readily made less lethal to reduce collateral damage in less-than-lethal applications. However, the forging and weld-overlay processes do not readily lend themselves to the formation of copper rotating bands on aluminum. But, the cold-spray process—which is equally efficient in the application of copper rotating bands on large and small volumes of munitions—can easily fabricate cold-sprayed copper rotating bands on aluminum substrates. Furthermore, it is believed the interfacial strength between the aluminum and cold-sprayed copper rotating band is stronger than the interfacial strength of traditionally fabricated (forging and weld overlay) copper rotating bands. The increase in interfacial strength results in the projectile being able to withstand a higher spin rate and/or a higher velocity at a reduced risk of slip (i.e., relative motion between the copper rotating band and the munition body).

This paper documents the initial efforts in demonstrating cold-sprayed copper rotating bands. The cold-spray fabrication process of the copper rotating bands is detailed in Section 2. The experimental demonstration of the cold-sprayed copper rotating bands is discussed in Section 3.

2. Cold-Sprayed Rotating Band Fabrication

The development of the cold-sprayed copper rotating band begins with the target substrate that the supersonic copper-particle stream impacts to form a bulk-deposited material that is subsequently machined to the final rotating-band dimensions. The copper particles are 99% copper and have diameters of a few hundred microns.² This copper rotating band is copper-rich compared to the M483A1 copper rotating band which is reported to use a copper alloy that is nearly 90% copper.³ The target substrate for this application is an aluminum (7075 alloy) base designed for a 155-mm artillery munition as shown in Fig. 3.



Fig. 3 Target substrate used to form cold-sprayed copper rotating band

The aluminum base has a circumferential channel machined into it to accommodate the cold-sprayed copper material. The dimensions of the channel are shown in “Detail B” of Fig. 4.

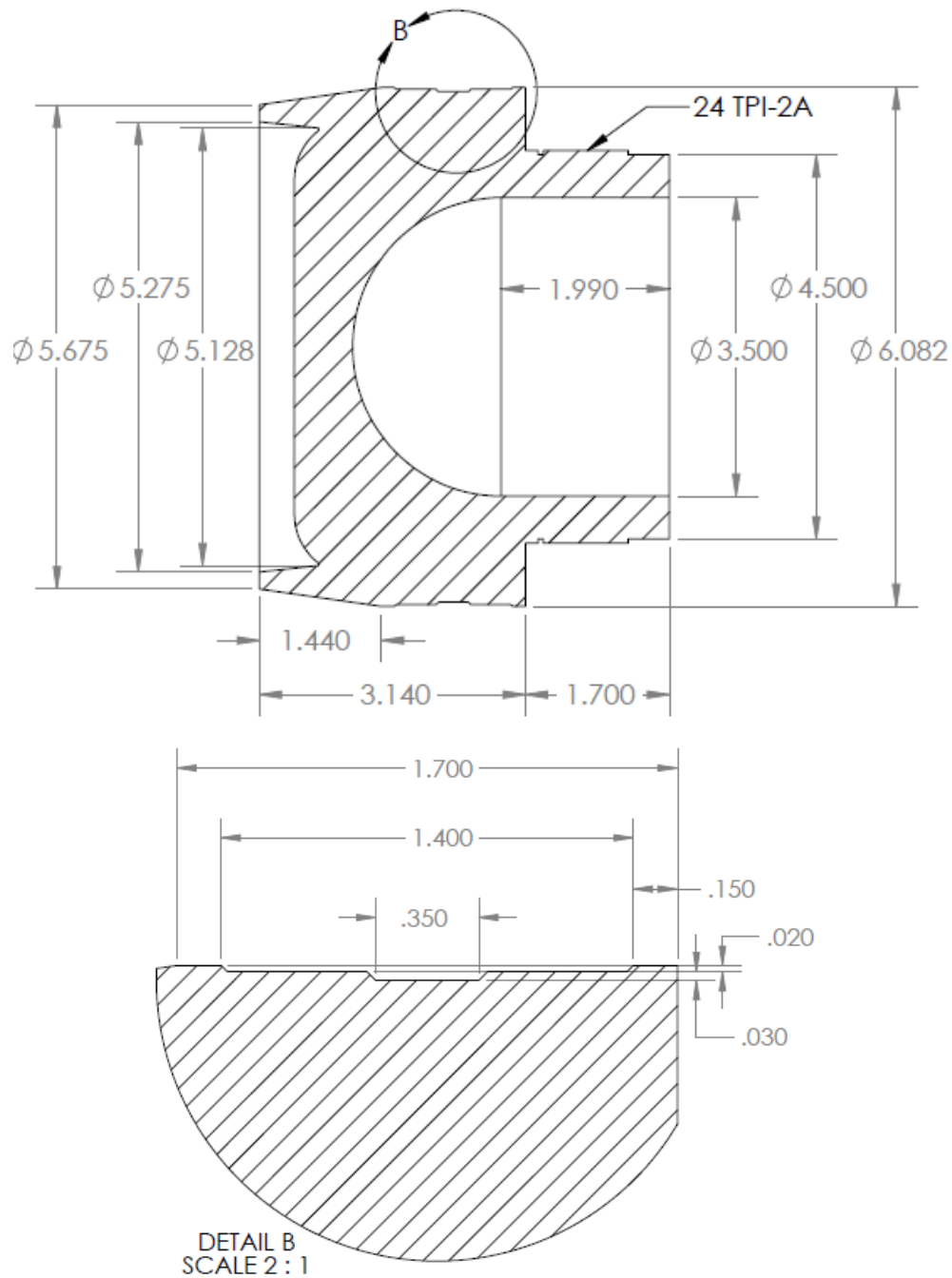


Fig. 4 Aluminum-base drawings, with circumferential-channel dimensions in Detail B; all dimensions are in inches and threads per inch (TPI).

The aluminum base is mounted into a computer numerically controlled (CNC) fixture that rotates the base as the copper particles are sprayed toward it. The CNC-aided supersonic nozzle deposits the copper particles onto the aluminum base as it traverses laterally across the channel width, as shown in Fig. 5.



Fig. 5 Deposition of copper rotating-band material onto aluminum (Al) base via cold spray at discrete times

The product of the cold-spray process is a bulk-deposited material as shown in Fig. 6. The material properties of the bulk-deposited copper material depend on the cold-spray process parameters, which include particle material (pure versus multimaterial powders), gas temperature, particle velocity, particle size, and particle shape.



Fig. 6 Cold-sprayed–bulk-deposited copper on aluminum base

The bulk-deposited material is larger than the final rotating-band geometry to allow machining the rotating-band profile to the drawing shown in Fig. 7.

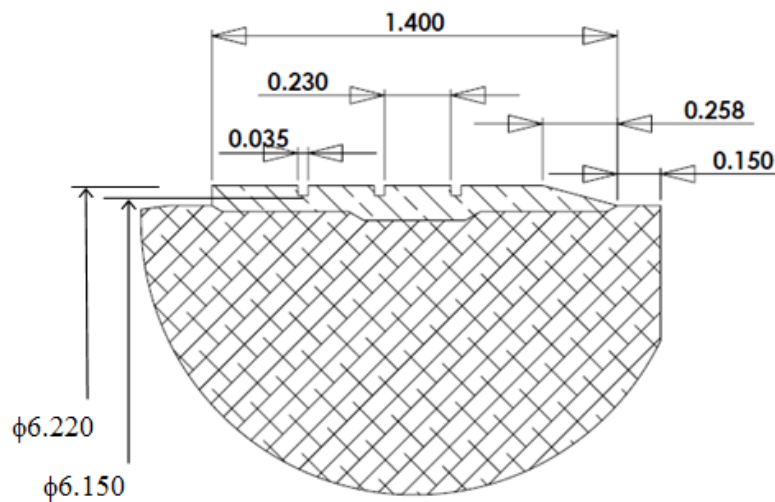


Fig. 7 Drawing of final copper rotating-band geometry (all dimensions in inches)

The finished copper rotating band is shown in Fig. 8. It is noteworthy that after machining 2 rotating bands, machine-shop personnel informed the author that the cold-spray material was brittle and flaked—large and irregular metal chips extended below the cutting surface—during machining of the rotating band. It was decided the 2 unmachined rotating bands would be removed (by machining) and that new material be deposited using a modified cold-spray process designed to increase in the ductility of the deposited-copper material. The resulting bulk-deposited copper rotating bands were machined to the final rotating-band geometry; the machine-shop personnel noted that these copper rotating bands, fabricated with the updated cold-spray process, machined like conventional copper alloys. Unfortunately, the identification of the bands was not tracked; therefore, it was not possible to identify which bands were fabricated from which cold-spray process.

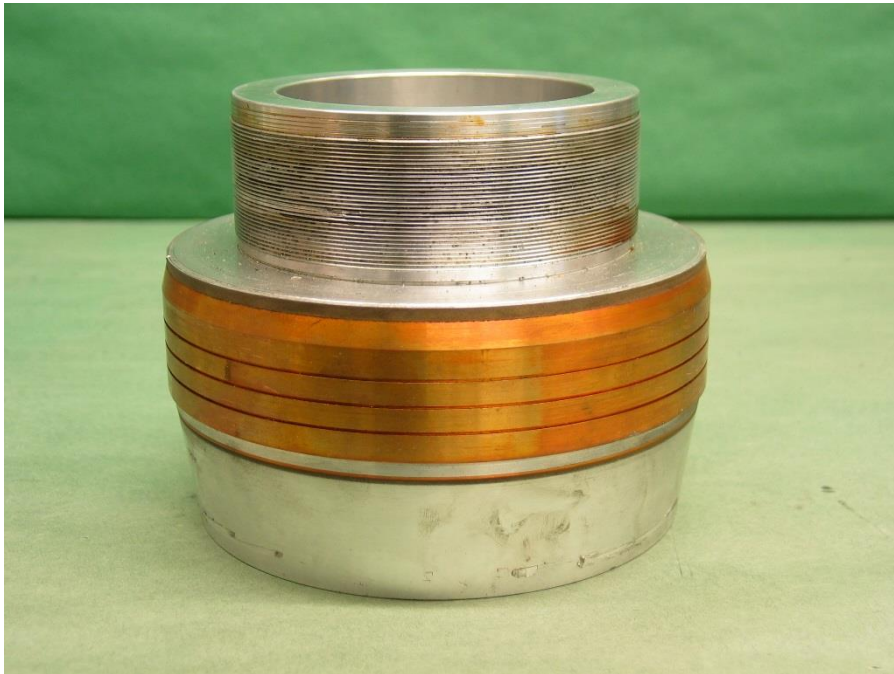


Fig. 8 Finished cold-sprayed copper rotating band machined from the bulk-deposited material

3. Experimental

The finished copper rotating band and aluminum-base assembly is threaded onto a billet of aluminum to form a demonstration test projectile whose rotational moment of inertia closely approximates that of the M483A1 155-mm artillery munition; however, it differs slightly in mass. The demonstration test projectile is shown in Fig. 9. Four demonstration test projectiles are fabricated and painted with alternating white and black, longitudinally oriented stripes to aid in the

visual spin-rate calculation. The spin rate is also measured using radar. The spin measurement is important because any projectile spinning at a rate significantly less than the kinematic spin rate, the spin rate dictated by the projectile velocity and the gun rifling, is surmised to have suffered a rotating-band failure during gun launch. Consequently, the projectile spin rate is an indirect measure of the robustness of the copper rotating band.

During testing, M483A1 munitions were used for charge establishment and verification of supporting test. Because the demonstration test projectile weighs approximately 3 pounds more than the M483A1, the demonstration projectiles were shot at various modified M4A2 zones in order to match the M483A1 projectile muzzle velocity and the projectile spin rate that were shot prior in order to define the camera settings.

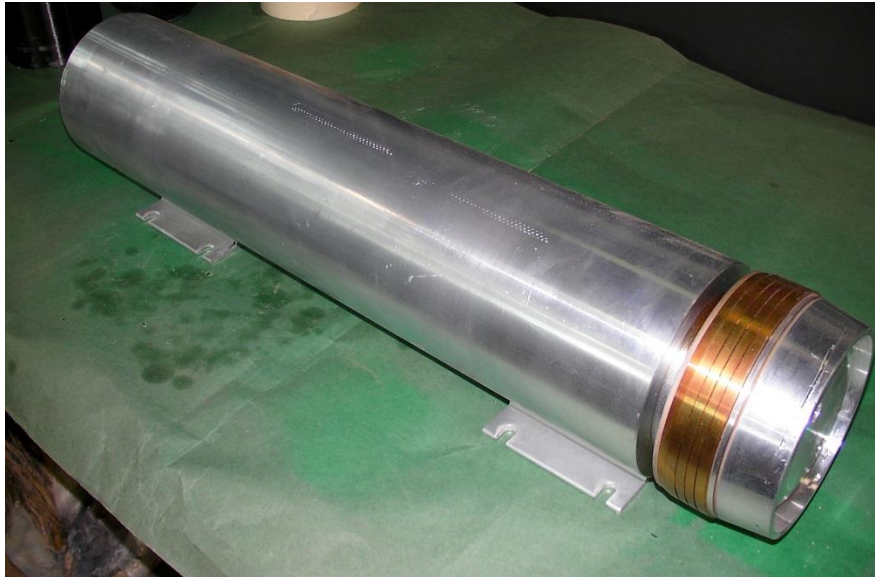


Fig. 9 Demonstration projectile (before paint) and partially fastened, comprising aluminum-base-copper cold-sprayed rotating band and solid aluminum forward body

The modified M4A2 zones are shown in the Table. The values in parentheses to the right of the identified zone indicate how much propellant was added (+) or removed (–) from the nominal M4A2-zone charge mass.

Table Demonstration test-firing log data

Shot	Projectile	Spin Rate			Absolute Error (%)	M4A2 Charge	Chamber		Muzzle Velocity (m/s)
		Kine (Hz)	Radar (Hz)	Visual (Hz)			Pressure (kpsi)	Charge (oz)	
1	M483A1	85.8	84.0		2.1	Z3 (−20 oz)	5.7	45.6	266
2	Demo	88.4	90.0		1.8	Z3 (−16 oz)	6.4	49.6	274
3	M483A1	93.9	92.0		2.0	Z3	7.8	65.6	291
4	Demo	88.7	Z3 (−10 oz)	6.9	55.6	275
5	M483A1	115.5	113.0		2.2	Z4 (−4 oz)	8.1	81.2	358
6	Demo	115.8	112.0		3.3	Z4	8.4	85.2	359
7	M483A1	164.8	165.0		0.1	Z6	15.8	157.4	511
8	Demo	165.5	...	178	7.6	Z6 (+4 oz)	16.0	161.4	513

The kinematic spin rate is determined from the relationship between the projectile velocity and the gun rifling defined by

$$\omega = \frac{2\pi}{\Gamma d} v, \quad (1)$$

where ω is the projectile spin rate (rad/s), Γ is the gun twist rate (caliber/revolution), d is the gun bore diameter (m), and v is the projectile velocity (m/s). The M199 gun tube is used in this experiment; the M199 has a diameter $d = 0.155$ m and features a constant 20-calibers-per-revolution twist rate (i.e., $\Gamma = 20$).

4. Results and Discussion

The projectile spin rates for the M483A1 (Shots 1, 3, 5, and 7) and the demonstration test projectile shot at 274 m/s and 359 m/s (Shot 2 and Shot 6, respectively) were measured by radar; their rates differed from the kinematic spin rate by less than 3.3%, indicating proper functioning of the rotating bands. However, the radar was unable to measure the spin rate of the demonstration test projectile for Shots 4 and 8, in which rotating-band failure was observed (Shot 8) and suspected (Shot 4). It is theorized that these 2 rotating bands were fabricated with the initial cold-spray process that was noted to lack ductility. For these shots, the spin rate was to be estimated using the high-speed video. However, the spin rate for Shot 4 is unknown because the high-speed cameras failed to trigger. The spin rate for Shot 8 is estimated to be 178 Hz, which is approximately 13 Hz greater than the kinematic spin rate and therefore judged to be inaccurate due to the difficulty in visually measuring the projectile angular position. However, this spin-rate estimate does indicate the projectile has a significant spin rate and that the copper rotating band was able to impart spin to the projectile. The linearity of

the projectile spin rate with projectile velocity is shown in Fig. 10. (The kinematic and measured spin rates are shown with the muzzle-exit velocities in the Table.)

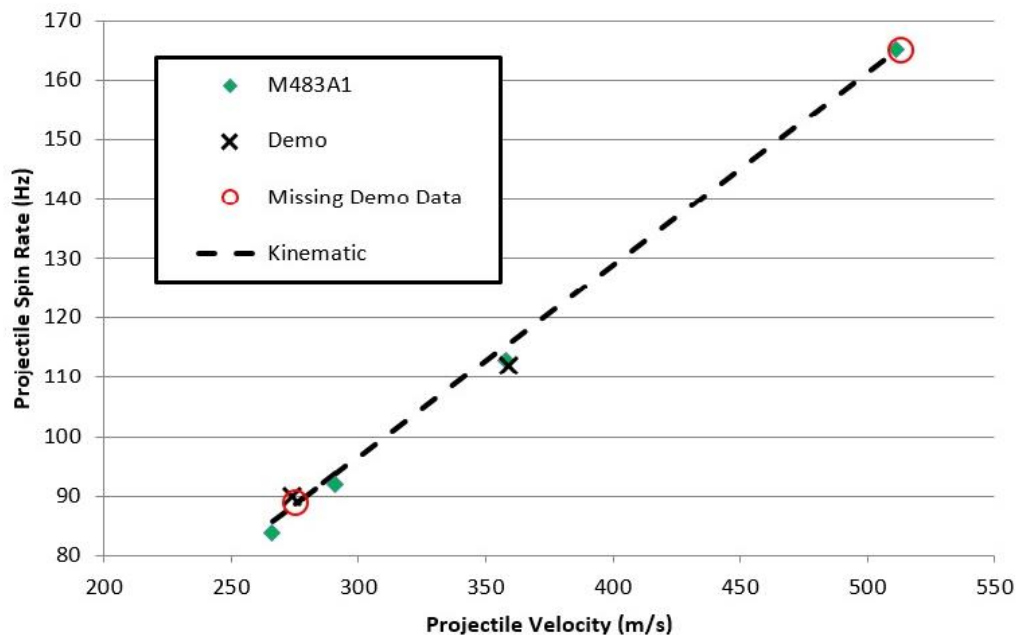


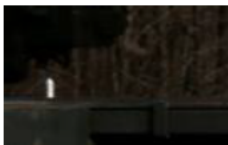
Fig. 10 Measured projectile spin rate's comparison with kinematic spin rate

The cold-sprayed copper rotating bands are shown to provide excellent obturation as there was little indication of propellant gas at or in front of the projectile—“leakage”—for any shot, excluding Shot 4 (cameras did not trigger). Further, the cold-sprayed rotating bands are shown to be structurally robust at relatively high charge masses; a sequence of images for Shot 8 is shown in Fig. 11, where the demonstration projectile is launched with a charge mass of 157.4 oz of propellant and achieves a muzzle velocity is 513 m/s. It is noted that the shiny object identified in Fig. 11d is believed to be a failed portion of the rotating band seen shortly after muzzle exit. Since the measured projectile-spin rate is nearly equivalent to the kinematic spin rate and no evidence of leakage was observed, it is believed the rotation band failed after muzzle exit in a tensile spall-failure mode due to the sudden unloading from a compressive stress state. Further, it is believed the 2 rotating bands that failed in this manner were fabricated using the initial cold-spray process that was noted to be brittle during machining of the bulk-deposited copper material.

(a)

(b)

(c)



(d)

Fig. 11 Discrete time of test Shot 8 at a) just before muzzle exit, b) just after muzzle exit, c) a few calibers after muzzle exit, and d) a few projectile lengths after muzzle exit with an unknown shiny object trailing the projectile

The evidence indicating partial structural failure of the copper rotating band *after* muzzle exit is from the recovered test projectile from Shot 8 (shown in Fig. 12). The engraving pattern on the rotating band on this test projectile is seen in the figure.



Fig. 12 Recovered test projectile (painted) from demonstration

Failure of the rotating band is seen in Fig. 13, as a portion of the copper-band material is missing; this missing portion of the copper rotating band is likely the “shiny object” identified in Fig. 11d.



Fig. 13 Cold-sprayed copper rotating band a) engraved on Side 1 and b) engraved with failure on Side 2

Lastly, the various steps of development of the cold-sprayed copper band are shown in Fig.14; from left to right: target substrate, finished copper rotating band–aluminum-base assembly, and post-shot engraved copper rotating band–aluminum-base assembly.



Fig. 14 Sequential development process (left to right) of cold-sprayed copper rotating band–aluminum-base assembly

5. Summary

Copper rotating bands fabricated using the cold-spray process have been successfully demonstrated for the first time. The development of the cold-sprayed copper rotating band substrate was an aluminum base. The copper particles were deposited onto this aluminum substrate to form the rotating band. The copper rotating band performed well as there was no evidence of leakage or in-bore failure. There was indication of a partial rotating-band failure corresponding to muzzle exit. It is believed this failure was largely due to the cold-spray process parameters used during the initial deposition of copper material, given the observation that these initial copper rotating bands tended to “flake” during machining. The cold-spray process’s parameters were altered and new copper rotating bands then were noted to have machined similarly to conventional copper-alloy materials.

6. References and Notes

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